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NOTCHED BEND BEHAVIOR OF BERYLLIUM OVER A WIDE RANGE OF STRAIN RATES

T. Nicholas

Air Force Materials Laboratory
Wright-Patterson Air Force Base, Ohio

December 1975

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METALS BEHAVIOR BRANCH
METALS AND CERAMICS DIVISION

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TECHNICAL REPORT AFML-TR-75-177
INTERIM REPORT FOR PERIOD SEPTEMBER 1973 – MARCH 1975

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AIR FORCE MATERIALS LABORATORY
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Air Force Systems Command
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NOTICE

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FOR THE COMMANDER

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FOREWORD

This technical report was prepared by the Metals Behavior Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. The research was conducted by Dr. T. Nicholas under Project No. 7351, Task No. 735106 during the period September 1973 to March 1975.

The author would like to acknowledge the significant contributions of Mr. Jim G. Paine, Systems Research Laboratories, Dayton, Ohio in the experimental portion of the investigation.

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SECTION I

INTRODUCTION

The development of new and improved structural grades of a beryllium is hindered by a lack of general agreement among structural designers and materials engineers as to what constitutes an acceptable criterion for ranking materials. Most attention has been devoted to uniaxial tension testing as a method of evaluating beryllium material behavior for structural applications, with a great deal of significance being placed on the magnitude of the uniaxial tensile strain or elongation to failure. The advantages of the tensile test as an acceptance test are the obvious simplicity of conducting the test and the ease of fabricability and relatively low cost of the test specimens. The question of the orientation of the test specimen with regard to the fabricated part is not to be regarded lightly, however, especially in the case of sheet material or thin-walled cones and frusta where through the thickness strains to failure are generally lowest of any orientation and generally difficult or impossible to measure directly.

For structural applications involving dynamic loading, the question of material ranking or acceptability for use in environment where high strain rates may be encountered poses additional problems. High strain rate tensile tests are more difficult to perform than quasi-static tests, require unique, sophisticated equipment and instrumentation, and are often difficult to interpret because of inertia and wave propagation and interaction effects at very high loading rates. One possible approach to materials screening and evaluation for dynamic loading applications is

some type of standard impact test, leading, in part, to the considerable attention devoted to instrumented Charpy impact testing of beryllium during the past several years. Because of the very low impact energy required to break notched or fatigue cracked beryllium bars in bending, instrumented impact testing is ideally suited to beryllium testing. The proper interpretation of the experimental values of impact energy, maximum load, or deflection, however, is difficult although the test is relatively easy to perform.

Freudenthal (Ref. 1) has pointed out that "no interpretation of the results of notched-bar impact tests in basic physical terms is possible... it can therefore not be reliably decided whether observed variations are the result of the differences in one or a number of geometrical factors, or whether they are the expression of differences in some intrinsic property of the material". The principal purpose of conventional notched bar impact testing is to detect changes from brittle to ductile behavior as temperature or velocity is changed and to identify transition temperatures or velocities. Thus, notched impact testing of beryllium under <u>fixed</u> conditions of impact velocity, temperature, and specimen geometry may be a poor, if not risky, method of comparing different grades of material. Unless the strain rate and notch geometry (and temperature) are closely related to those encountered in structural applications, the notched bend impact test falls short of being an adequate screening test for this material. In order to identify possible transition velocities or temperatures, additional information on the variation of mechanical properties with strain rate and temperature is required. The fact that beryllium is rather brittle at room temperature makes this task even more difficult.

In a previous paper (Ref. 2) a technique was presented for conducting instrumented impact tests on beryllium using a modification of a Hopkinson bar apparatus. Over a range of impact velocities from approximately 0.5 to 5.0 m/sec, this technique allows the determination of the complete force-displacement history of the specimen from which quantities such as total energy, maximum load, and maximum displacement are easily obtained. The technique helped establish the validity of instrumented impact tests for materials having very low impact energies such as beryllium. To investigate the applicability of notched bend impact testing as a material screening test for beryllium, the Hopkinson bar technique and a standard hydraulic testing machine were used to obtain the response of notched bend specimens over a very wide range of loading velocities at room temperature. Data obtained for six different grades of beryllium are presented and interpreted in terms of their significance for structural applications and their relationship, if any, to the fundamental mechanical properties of beryllium.

SECTION II

MATERIALS AND EXPERIMENTS

Quasi-static and intermediate rate three point bend tests were performed on a MTS closed-loop, servo controlled hydraulic testing machine capable of generating constant crosshead velocities up to approximately 0.1 m/sec. A fixture consisting of a standard ASTM loading head and support mounted to the testing machine, shown in Fig. 1, ensures precision alignment of the specimen and loading head. Load and displacement or deflection are plotted on a X-Y recorder at slow rates of loading and on an X-Y oscilloscope at higher rates. Load is obtained directly from the load cell on the MTS machine while deflection is obtained from an LVDT mounted on the loading fixture.

For the dynamic tests, a Hopkinson pressure bar impacted by a striker bar is used to load the notched bend specimen as shown schematically in Fig. 2. The specimen is supported by a fixture having the same geometry as for the static case, while a loading tup of the proper geometry is attached to the end of the pressure bar in contact with the specimen. Strain gage signals from the pressure bar proportional to the incident and reflected pulse from the specimen are used to reconstruct the entire force-time and velocity-time history of the specimen. From this data, a load-displacement curve can be constructed from which energy, and maximum load and displacement can be obtained as in the quasi-static case. A complete description of the apparatus and instrumentation used for the dynamic testing as well as a discussion of the assumptions and accuracy involved are presented in Ref. 2.

The axes of the specimens are in a plane normal to the cylinder axis and the specimens are oriented such that an axis along the length of the notch is parallel to the axis of the solid cylinders or parallel to the radial direction in the hollow cylinders. The tensile stresses across the notch due to applied bending forces are thus in the transverse (T) direction of the solid pressings and in the circumferential (C) direction of the hollow pressings.

Beryllium produced by three different consolidation techniques was tested in three point bending over a range in loading velocities covering nearly seven orders of magnitude. Two grades of hot pressed block, a conventional structural grade S-200E and a chemically purified grade from impact attritioned powder, S-65, were obtained from Brush Wellman Inc. for testing. Two grades of plasma consolidated beryllium, designated "D" and "DD" were fabricated by Union Carbide Corporation Linde Division by plasma spraying and sintering. The two grades differed only in the post-sintering heat treatment. Two grades of hot isostatically pressed beryllium, one from commercial grade powder P-10, and one from high purity electro-refined powder, P-1, were obtained from Kawecki Berylco Industries. The chemistries of all the materials are given in Table 1. The billets for the hot pressed and hot isostatically pressed grades of beryllium were in the form of solid right circular cylinders. The plasma consolidated billets were in the form of thick walled (approximately 25 mm) circular cylinders. All specimens were machined and etched to the dimensions shown in Fig. 3; the notches were put in by electrodischarge machining before etching.

In addition to the bend specimens, mini-bar tensile specimens were machined from the same billets in accordance with the dimensions and

specifications of Fig. 4. The orientation of the axis of the specimens coincided with the direction of tensile stresses across the notch in the bend specimens, i.e. T direction for the solid cylinders and C direction for the plasma consolidated hollow cylinders. The tensile bars, having an effective gage length of approximately 15 mm, were tested in a standard 50 KN Instron testing machine using a cross-head rate of approximately .005 mm/sec. The data were recorded on an Instron strip chart recorder and reduced to stress-strain curves with the aid of a Hewlett Packard Model 9820A calculator, digitizer, and plotter system.

Load on the notched bend specimens in the quasi-static and intermediate rate tests was calibrated on the MTS machine using a proving ring and checked before and after each test series by shunting known calibration resistors across one arm of the strain gage bridge on the load cell. It is estimated that the measured load values were accurate to better than ±2%. A measure was made of the friction force in the fixture by running a series of tests at different crosshead rates using no specimen. It was determined that the measured friction forces were negligible at the quasi-static rates and increased to approximately 100N at the highest rate which is equivalent to only a few percent of maximum load for the samples tested.

Displacement of the loading head relative to the support fixture was measured with a linear variable differential transformer (LVDT) rigidly attached to the support fixture and contacting a rigid plate on the loading head as can be seen in Fig. 1. In this manner, the actual deflection of the specimen was obtained without having to correct for machine deflection.

The LVDT was calibrated with a dial gage; the accuracy of the deflection measurements is estimated to be better than $\pm 2\%$.

The strain gages on the Hopkinson bar apparatus used for the dynamic tests were calibrated by relating the measured velocity of a striker bar to the resulting stress wave amplitude using the experimentally measured elastic constants of the Hopkinson bar material. The accuracy of the load-deflection data obtained using the Hopkinson bar technique is dependent upon a number of factors including input velocity, ratio of incident to reflected pulse amplitudes, and others which are discussed more completely in Ref. 2. The raw data from the Hopkinson bar tests were also reduced with the aid of a calculator, digitizer, and plotter system.

SECTION III

RESULTS AND DISCUSSION

Typical uniaxial stress-strain curves for the six grades of beryllium tested are presented in Fig. 5. The curves were drawn to best fit the average of ten stress-strain curves obtained for each material. There was very little scatter from test to test on each of the six materials. The average values of ultimate tensile strength and total elongation to failure from the ten tests for each material are presented in Table 2. In each case, the orientation of the tensile specimen was with the axis in the transverse or circumferential direction as described previously so as to coincide with the direction of tensile stresses across the root of the notch in the bend specimens.

Total energy to failure, maximum load, and maximum deflections for the notched bend tests are plotted as a function of loading velocity in each of Figs. 6 through 14. In every case failure occurred by brittle fracture, there being no tearing or additional yielding after maximum load had been reached. Typical load-deflection curves at the slowest loading rates are presented in Fig. 15. The curves show variations in specimen stiffness or compliance as measured by a secant modulus to any point on the curve among the six materials tested. The D, DD, and S-65 specimens appear to be stiffer than the P-1, P-10, and S-200E samples. An examination of the uniaxial tensile curves for these materials shows no apparent correlation between the tensile data and the notched bend data, both taken at quasi-static loading rates, as far as general shape of load-deformation

curves. The region near the origin of the bend test curves, as can be seen from Fig. 15 is nearly identical for all six materials. If one considers a value of 200 MPa as a reasonable value for an average yield strength of the six materials tested (Fig. 5) and an elastic stress concentration factor of 2.25 for the notch geometry used calculated from Petersons tables (Ref. 3), one can calculate the load beyond which elastic behavior is no longer a valid assumption. Using elementary beam theory based on the net cross-sectional area and assuming identical behavior (elastic) in tension and compression, a value of approximately 1 KN is obtained for the load at which yielding starts to occur. The deflection of the specimen at this load level, of the order of .025 mm, is certainly well within the measuring accuracy of the instrumentation. However, the deflection measured also includes some contribution due to local deformation or indenting under the loading head and at the supports on the beam. The magnitude of this local deformation cannot be estimated but amounts of the order of .01 mm or greater certainly would not seem unreasonable at loads of the order of 1 KN. Thus, no accurate measurement of the slope of the load-deflection curve can be made with any confidence in an attempt to correlate that slope with the elastic modulus of beryllium through a beam stress and deflection analysis. In addition, the transducer measuring deflection is not located along a line parallel to the axis of the beam specimen. It thus will record any deflections due to bending of the fixture about the specimen axis. Although the fixture is aligned and guided very precisely, extremely small bending deflections are still observed and show up as small variations in the slope of the load-deflection curve from test to test.

From the previous calculations, it can be seen that the major portion of the load-deformation curve is determined by the nature of the plastic deformation of the beryllium at the root of the notch where a stress concentration is present. Thus, the actual shape of the uniaxial stress-strain curve into the plastic region, or the governing flow law for multiaxial stresses, governs the deformational behavior of the notched beam. A detailed elastic-plastic stress analysis of a notched beam in bending would be required to accurately predict the beam deformations.

If we continue to confine our attention to quasi-static behavior, we can interpret the maximum loads in terms of an approximate value for maximum strain or stress using a simplified beam analysis. Assume, for simplicity, perfectly plastic linear strain hardening behavior as depicted by the dashed lines in Fig. 16 for the tensile and compressive uniaxial stress-strain behavior of P-1 and S-65. Assuming a linear variation of strain across the cross-section at the notch (plane-sections remain plane), a state of pure bending, and uniaxial stresses only, we can calculate the maximum tensile and compressive strain as a function of the bending moment or the applied load. The results of these calculations are shown in Fig. 17. If we take average values for the maximum load at quasi-static rates from Figs. 9 and 11 as 6.4 KN for S-65 and 7.4 KN for P-1, we obtain values of 3.1% and 2.1% for S-65 and P-1, respectively, as the maximum tensile strain at failure from Fig. 17. These calculations, subject to the approximations discussed, do not consider the effect of the stress concentration. However, they do give what appears to be reasonable estimates for strain to failure in these two materials.

If one compares the maximum load values for the six materials with the ultimate tensile strengths in uniaxial tension, a trend can be seen. These values, presented in Table 2, show the materials to rank in nearly the same order in ultimate tensile stress as in maximum load in notched bending. Note, from Figs. 9, 10 and 11, the relatively large amount of scatter in the load values from which these averages were approximated. Further examination of the quasi-static data presented in Table 2 shows, however, no apparent correlation between uniaxial strain to failure and (average) maximum deflection in the bend tests. This finding is consistent with observations in notch tensile testing of beryllium where no correlation was found between notch ductility ratio, a measure of plasticity in the vicinity of a notch, and uniaxial strain to failure (Ref. 4). Thus these data also indicate that failure under tensile stresses in the presence of stress concentrations is a complex phenomenon that cannot be explained on the basis of uniaxial tensile data alone.

Figures 9, 10 and 11 present the maximum load in the notched bend tests as a function of loading velocity. With the exception of the D material, all materials show basically no change in maximum load as a function of velocity. The loading velocity is related, in some manner, to the strain rate in the specimen. Since the stress-strain curves for all these materials are relatively flat in the plastic region (Fig. 5), percentage changes in the strain to failure would alter the ultimate stress by much smaller percent as the failure point moved along the curve in the plastic region. Combined with the fact that the flow stresses at a given strain in beryllium increase with increasing strain

rate (Ref. 5), it is to be expected, then, that the failure stresses in beryllium will remain fairly constant with strain rate or loading velocity in the case of the bend tests. The exception to this case is the D material where an extremely large decrease in strain to failure or deflection of the bend specimens (Fig. 13) moves the failure point closer to the origin and results in lower maximum loads at higher strain rates.

The other two quantities, maximum deflection and total absorbed energy, are essentially dependent upon one another by virtue of the fact the maximum loads do not vary with velocity for any one material. We can thus concentrate our attention on the curves of energy to failure as a function of loading velocity as shown in Figs. 6, 7, and 8. The fitted piecewise linear curves of these three figures are replotted as a single plot for ease of comparison in Fig. 18. Two distinct types of behavior can be seen among the six materials tested. The S-65 and DD materials show a very slight drop of approximately 10 percent in total energy with increasing velocity over the range of loading velocities covered in these tests. The drop is gradual and may be due, solely, to experimental accuracy, especially at the highest velocities, or material scatter as can be seen in any narrow range of velocities. For these two materials we can conclude that there is no significant degradation of mechanical properties in notched bending up to the maximum impact velocity of approximately 5 m/s. The remaining four materials show a definite decrease in absorbed energy within the velocity range of these experiments. The D material shows the lowest impact energy of approximately .4J at the higher velocities.

The P-1 material has an impact energy of approximately .9J at the highest velocities, approximately the same as the DD material, yet significantly below the quasi-static value of slightly less than 1.6J. The energy drop in all four materials appears to occur over a fairly narrow range of loading velocities although there is a relatively large amount of scatter and there are few data points in the transition range, especially for the S-200E beryllium. The D material showed the lowest transition velocity of approximately 10^{-4} m/s as well as the lowest energy at higher velocities and the greatest percentage decrease in energy of about 65 percent over the entire velocity range. The other three materials showing a marked decrease in energy, P-1, P-10, and S-200E, all appear to have a transition velocity in the vicinity of 10^{-1} m/sec or slightly lower. Although the term transition velocity may be applied to this abrupt and noticeable change in behavior, it is not what is normally considered a transition velocity from a ductile region to a brittle region. In the case of these grades of beryllium it is more of a change from brittle to even more brittle behavior at room temperature. Note the low values of absorbed energy for these specimens using a relatively smooth notch with an elastic stress concentration factor of only 2.25. An examination of the curves of maximum deflection as a function of velocity, Figs. 12, 13 and 14, reveals the same trends as the energy curves. Again, the S-65 and DD materials show no significant decrease in deflection to failure with increasing velocity while the remaining four materials show a marked decrease at a fairly well defined transition velocity.

There has been discussion and speculation within the beryllium community over the effects of yield points in uniaxial tension stress-strain curves on the biaxial and high strain rate response of beryllium. It is generally felt that materials with well defined yield points have low strains to failure under biaxial tension stress states and at high rates of strain. The material with the highest and most well defined yield point, D, as can be seen in Fig. 5, exhibited the most pronounced drop in energy with increasing velocity. The S-200E grade, also exhibiting a well defined yield plateau in tension, showed a drop in energy of over 50 percent of the quasi-static value at high strain rates. The two materials with not so well defined yield plateaus or yield inflections, DD and S-65, showed the least sensitivity to loading velocity. The two materials showing no apparent yield point behavior, P-1 and P-10, however, did show significant decreases in energy with increasing velocity.

The strain hardening behavior of the six materials tested was quite similar throughout most of the plastic region at quasi-static rates as can be seen from Fig. 5. There is no apparent clue in the shape of these curves as to the existence of a transition velocity and a decrease in absorbed energy in notched bending with increasing velocity.

A large amount of data on P-1, S-65, and DD beryllium grades in uniaxial tension has been obtained covering a wide range of strain rates up to approximately $500 s^{-1}$ (Ref. 5). These data show only a slight decrease in strain to failure with a corresponding increase in flow stress with increasing strain rate for all three grades. There is no apparent evidence of a transition strain rate in the uniaxial tension case as was observed

in the bend tests for P-1 beryllium, although there is a trend towards lower average values at the highest strain rates, especially for P-1 and somewhat less for DD. The highest strain rate tests occurred in a time of approximately 50 μsec, which is the same length of time involved in the bend tests at the highest impact velocities. It can thus be estimated that the highest local strain rate in the bend tests was of the same approximate magnitude as the maximum strain rate in the tensile tests. The existence of a transition velocity in the bend tests would appear to indicate that there are additional factors influencing failure in the presence of notches other than tensile strain rate.

SECTION IV

CONCLUSIONS

Notched bend tests over a wide range of velocities on six grades of beryllium have been used to identify transition velocities at which significant decreases in absorbed energy are observed with increasing velocity for four of the six materials. The significance of this transition velocity is not clear since we are dealing with materials which exhibit brittle fracture both below and above the transition velocity. In all cases, the absorbed energy is very small compared to that for most structural materials. Even if the transition velocity can be identified or the energy absorbed can be determined at a single reference velocity, the implications of the numerical values of energy absorbed are not clear. At impact velocities of 1 m/s or slightly higher, we observe that P-1 and DD berylliums respond in approximately the same manner, yet the energy to fail P-1 at this high velocity is slightly more than half the energy to fail it at quasi-static loading rates. The DD material, on the other hand, shows hardly any change in energy with velocity over the entire range of velocities covered in the tests. The significance of the actual numerical values for energy, maximum load, or maximum deflection is certainly not clear from a structural designer's point of view. If an impact test or a slow bend test on a notched bar is to be used as a screening or acceptance test for beryllium, it is obvious from the data presented that the loading velocity should have some relationship to the (maximum) loading rates to be encountered in actual use.

The D or P-10 materials, for example, would appear to be as acceptable as the other four grades if only quasi-static load rates are to be encountered. At higher rates, these materials would appear to be less acceptable. The other factor to consider in using a notched bend test is the state of stress in the specimen. Whether or not this stress state has any relationship to the stresses in the actual structure is an important point to consider. As has been observed, beryllium and other materials appear to behave differently in notched bending or notched tension than in uniaxial tension. It is important, therefore, to carefully consider the strain rate and state of stress before adopting any material evaluation test technique for beryllium.

Finally, it must be noted again that all data reported here were obtained on specimens of identical geometry. Thus, only a single stress concentration in bending was used. The same transition velocities may not necessarily be obtained for different notch geometries. The effect of stress concentration on the behavior of beryllium in bending is a topic that is under consideration at present and will be the subject of a future technical report.

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3. R. E. Peterson, Stress Concentration Design Factors, Wiley, New York, 1953.

4. T. Nicholas and G. R. Atkins, Notch Tensile Strength of Advanced Structural Grades of Beryllium, AFML-TR-74-252, Wright Patterson AFB, Ohio, April 1975.

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TABLE 1

CHEMICAL ANALYSIS (PPM)

Element	Grade Lot Number	S-65 1902	S-200 0641	P-1 T-223	P-10 T224B	D, DD
Al		190	800	40	340	70
C		250	1300	120	800	214
Cr		60		20	60	110
Cu		40		20	35	150
Fe		580	1600	280	950	830
Mn		20		8	160	190
Ni		40		100	85	200
Si		170	300	60	160	240
Ti		100				110
Mg		-20	100	10	180	
BeO(%)		.53	1.8	.97	1.11	1.45

TABLE 2

QUASI-STATIC MECHANICAL PROPERTIES

Material	Notched bend test		Tensile Test	
	Max load (KN)	Max defl. (mm)	UTS (MPa)	Elong (%)
S-65	6.36	.282	372	5.60
S-200E	7.12	.345	395	2.95
P-1	7.43	.333	444	4.37
P-10	7.25	.287	440	3.41
DD	6.85	.262	415	4.83
D	7.34	.244	431	5.02

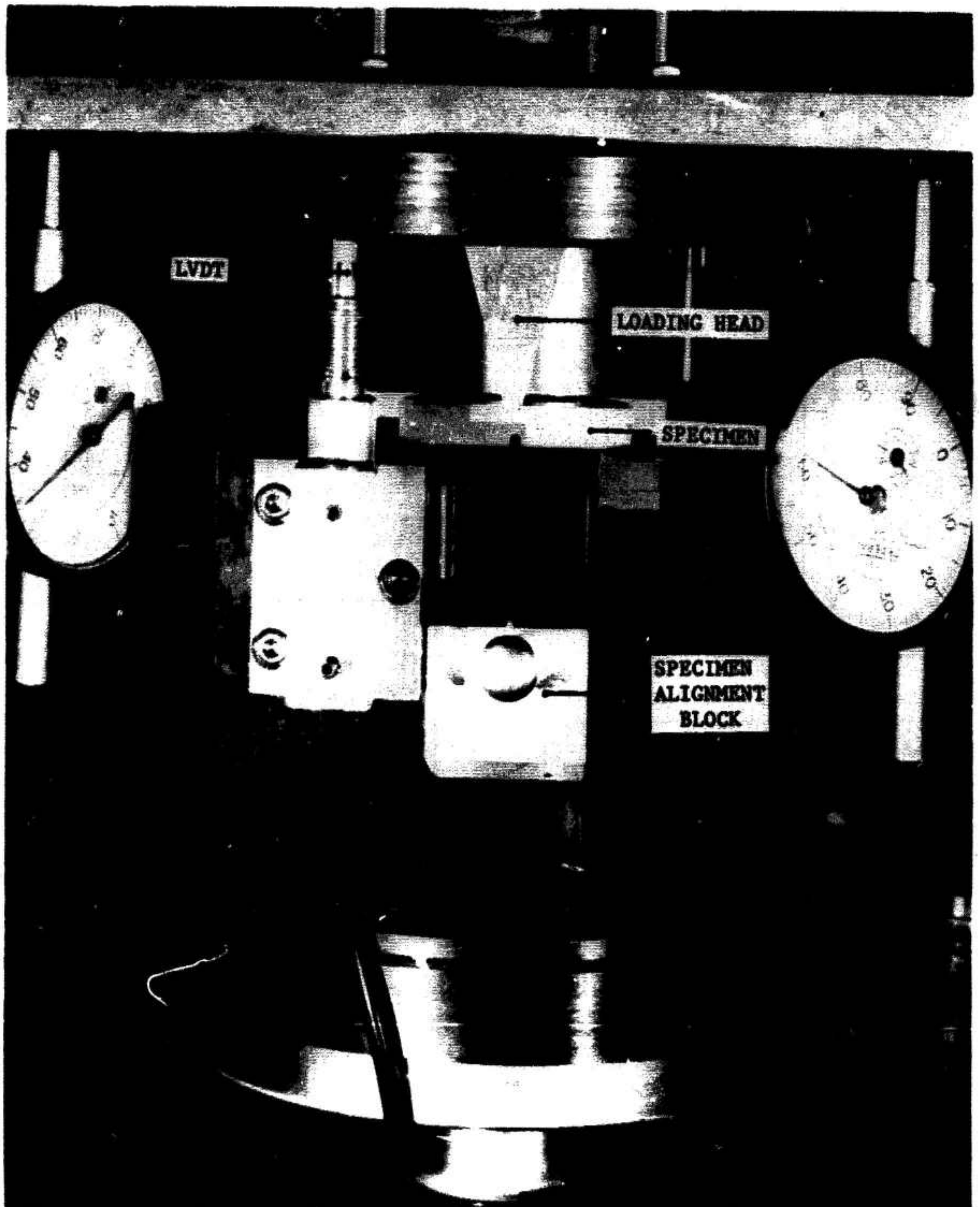


Figure 1. Three Point Bend Test Fixture

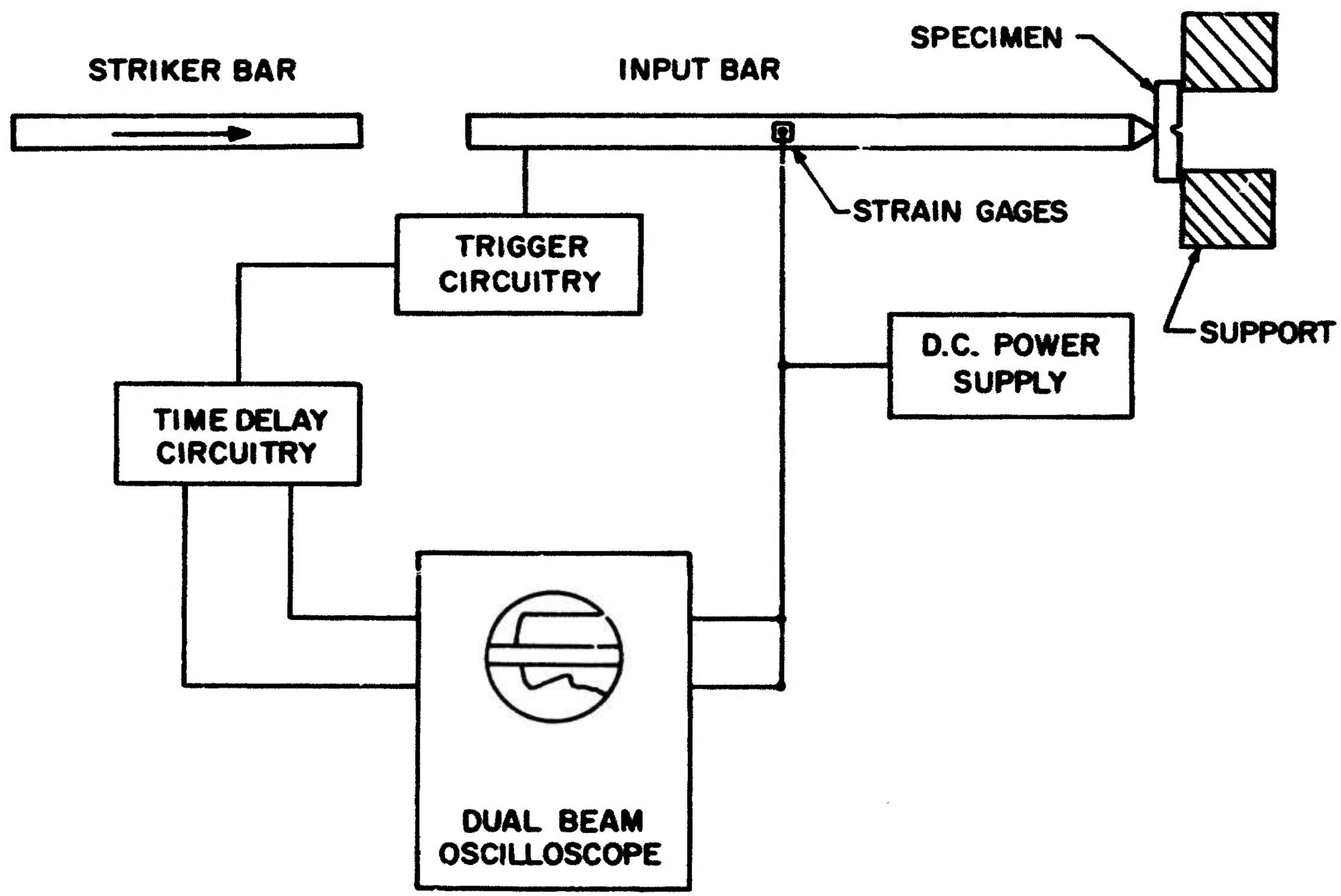


Figure 2. Schematic of Hopkinson Bar Setup

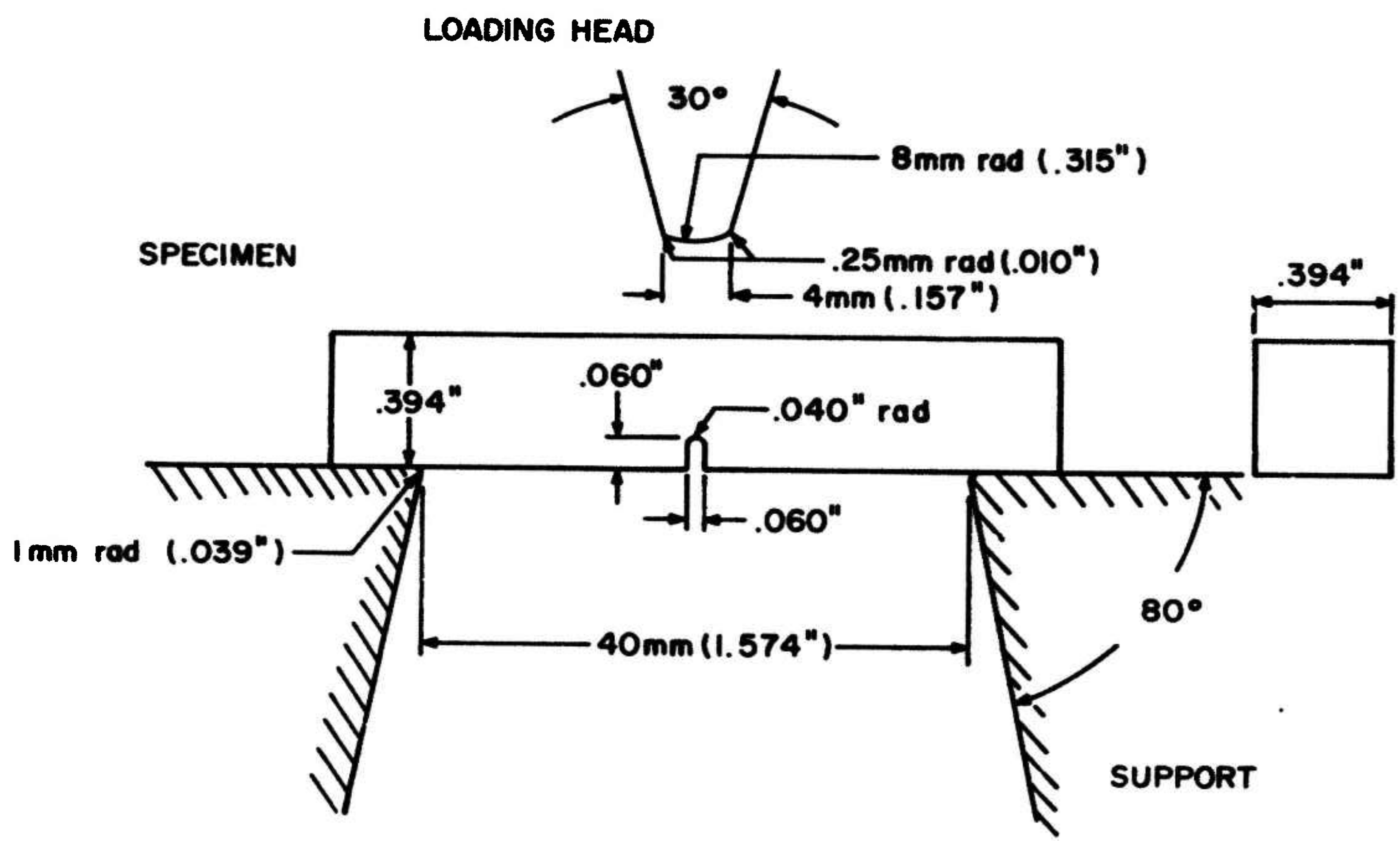
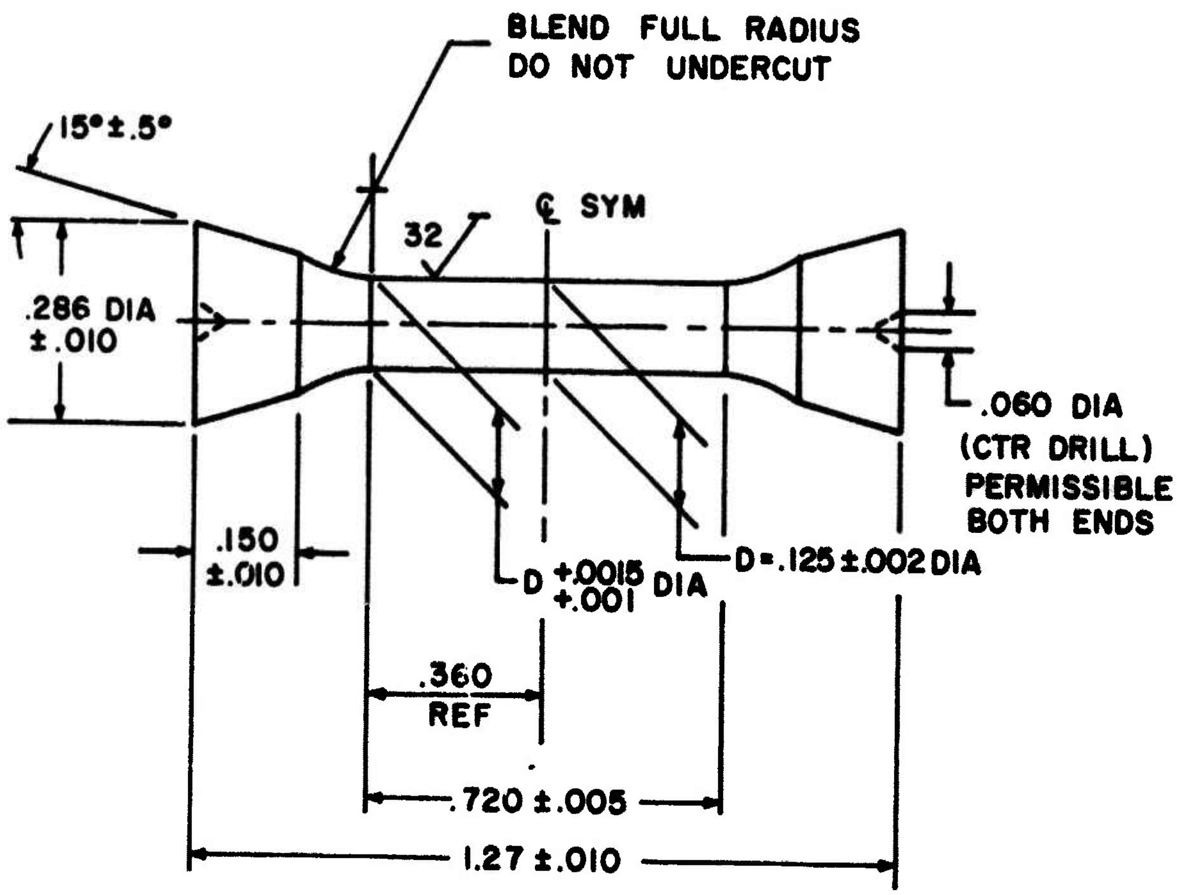


Figure 3. Beryllium Notched Bend Specimen



NOTES:

1. ALL DIMENSIONS IN INCHES AFTER ETCHING
2. FINAL MACHINING CUT NOT TO EXCEED .003"
3. ETCH TO REMOVE .004" ± .0005" (.008" ON DIA)
4. FINISH REQUIREMENT MUST BE MET AFTER ETCHING

Figure 4. Mini-bar Tensile Specimen

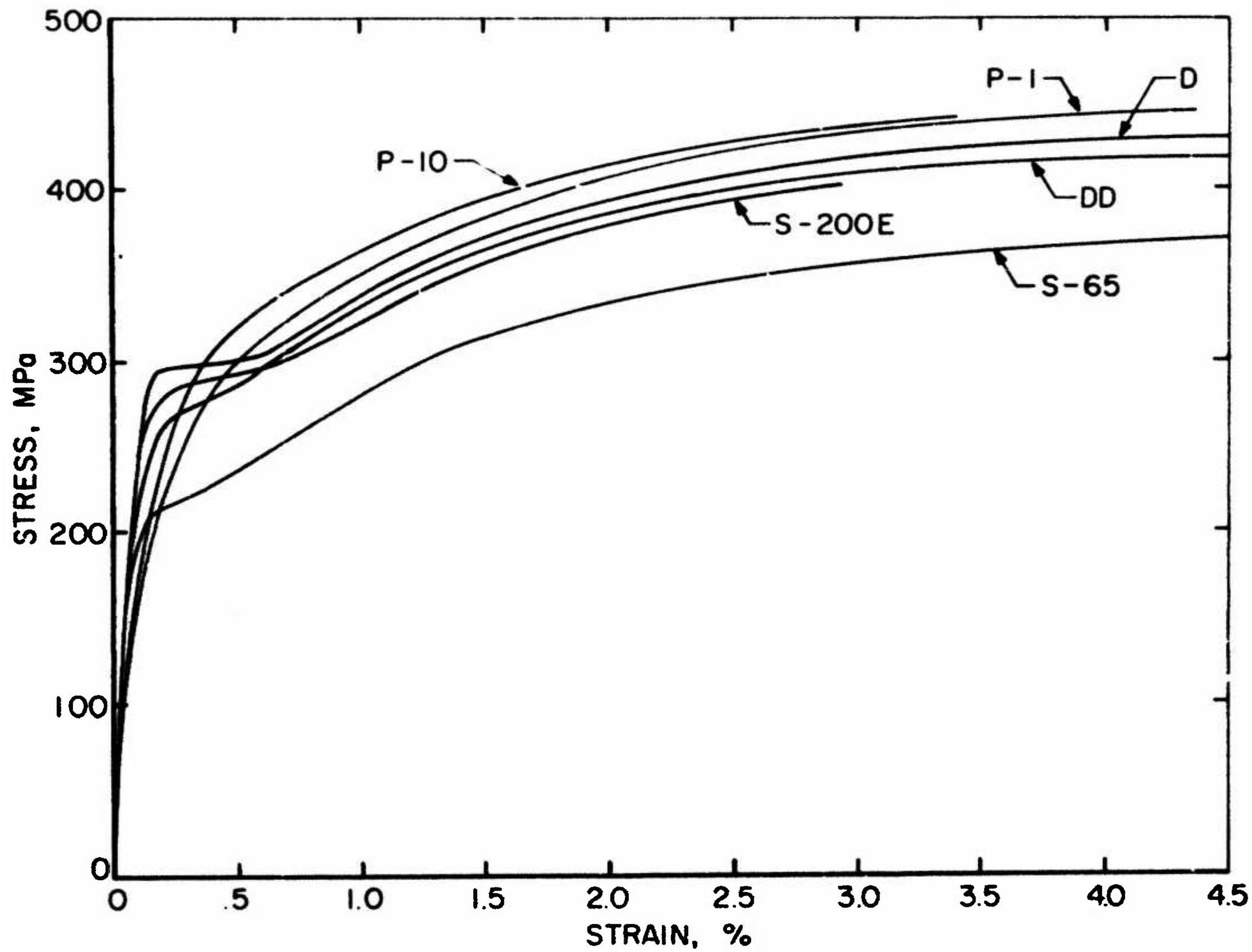


Figure 5. Uniaxial Tension Stress-Strain Curves

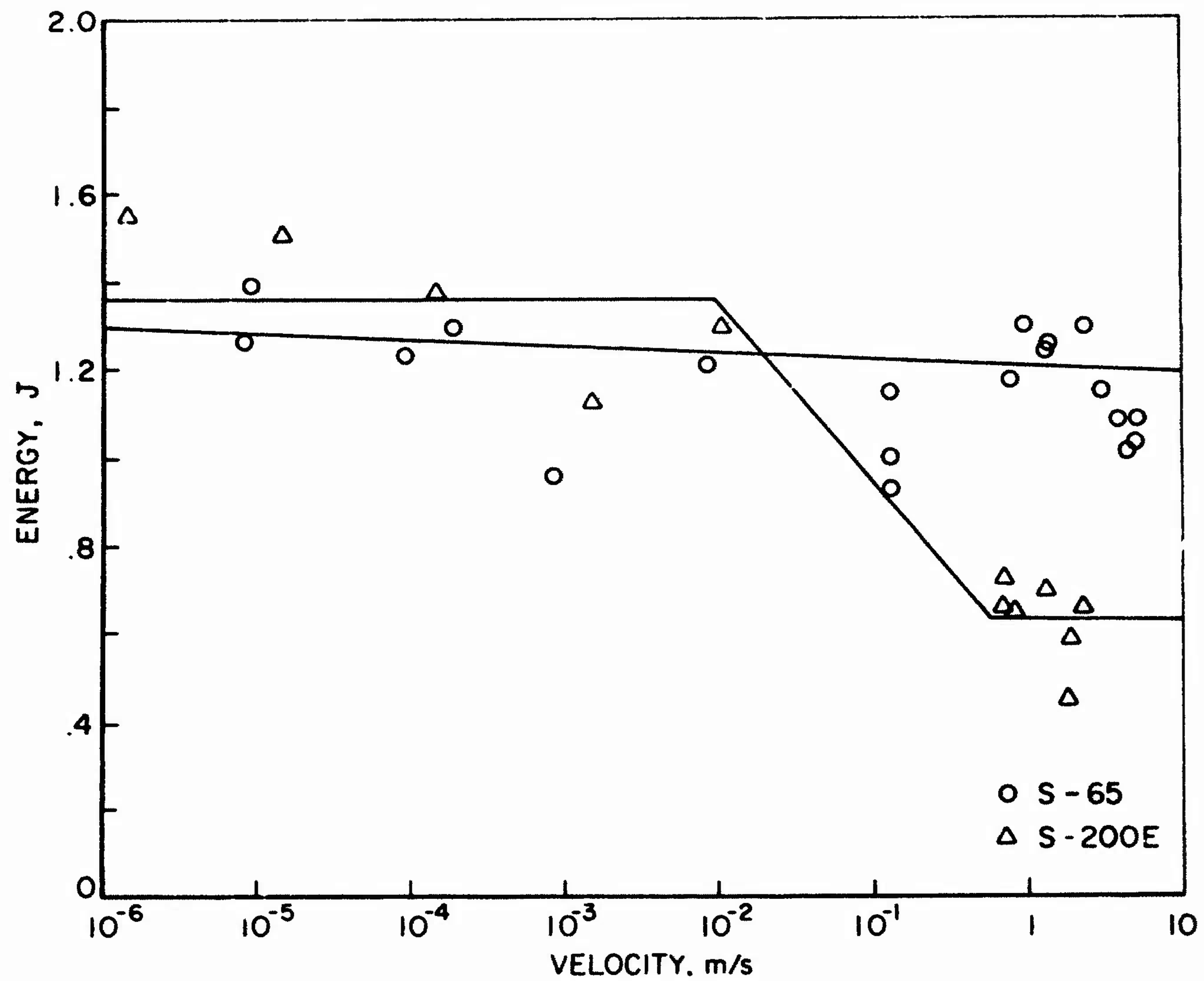


Figure 6. Absorbed Energy, S-65 and S-200E

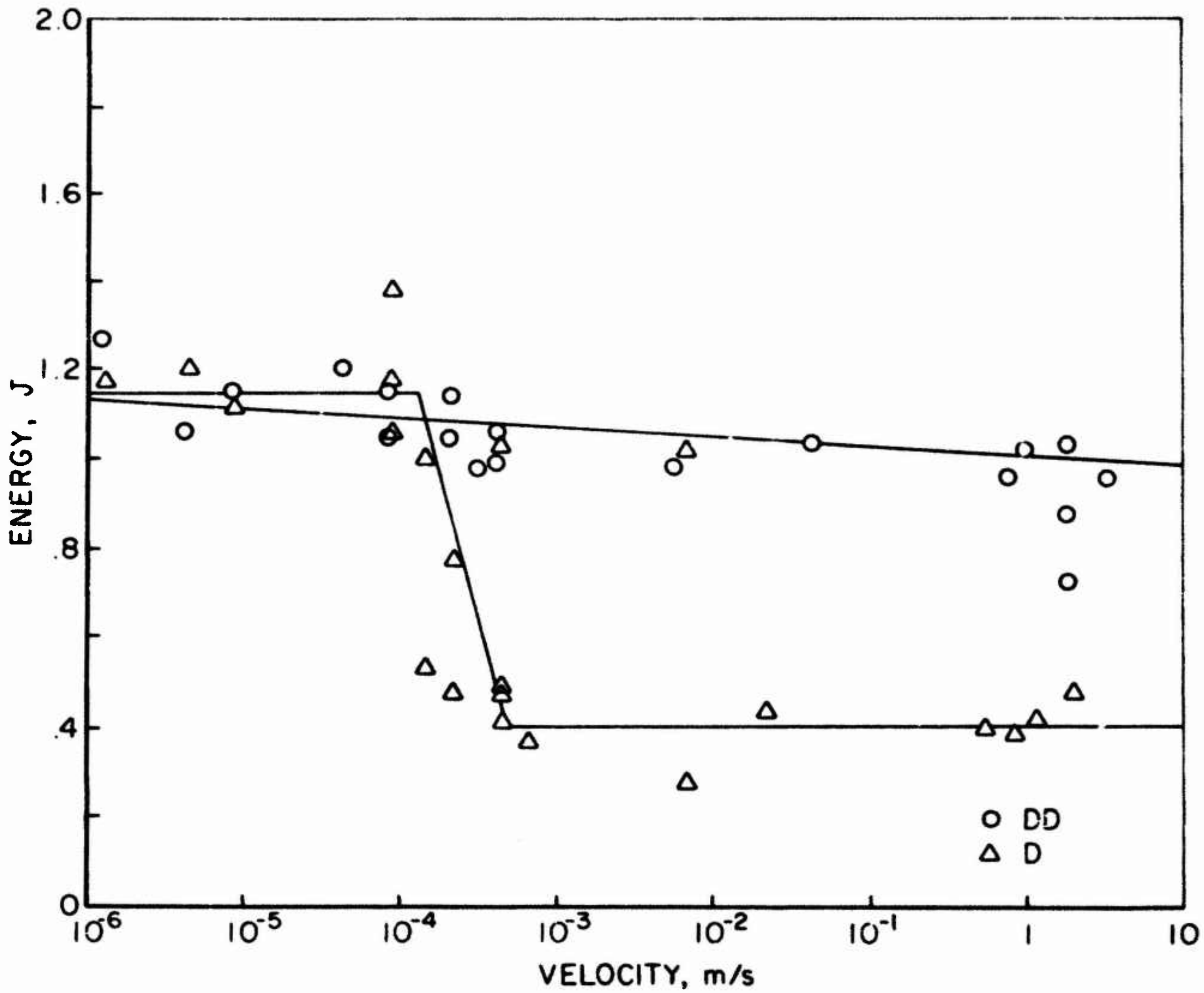


Figure 7. Absorbed Energy, D and DD

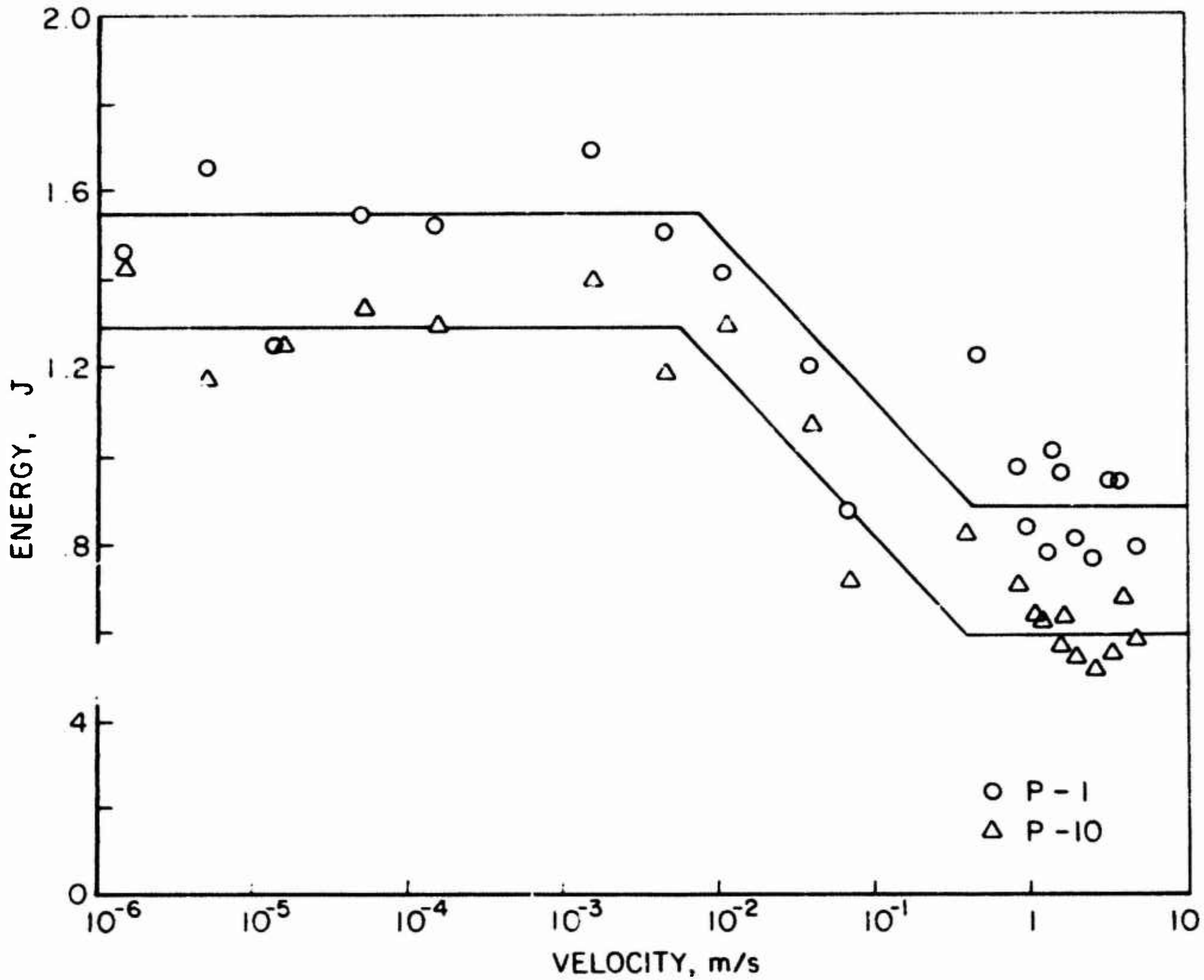


Figure 8. Absorbed Energy, P-1 and P-10

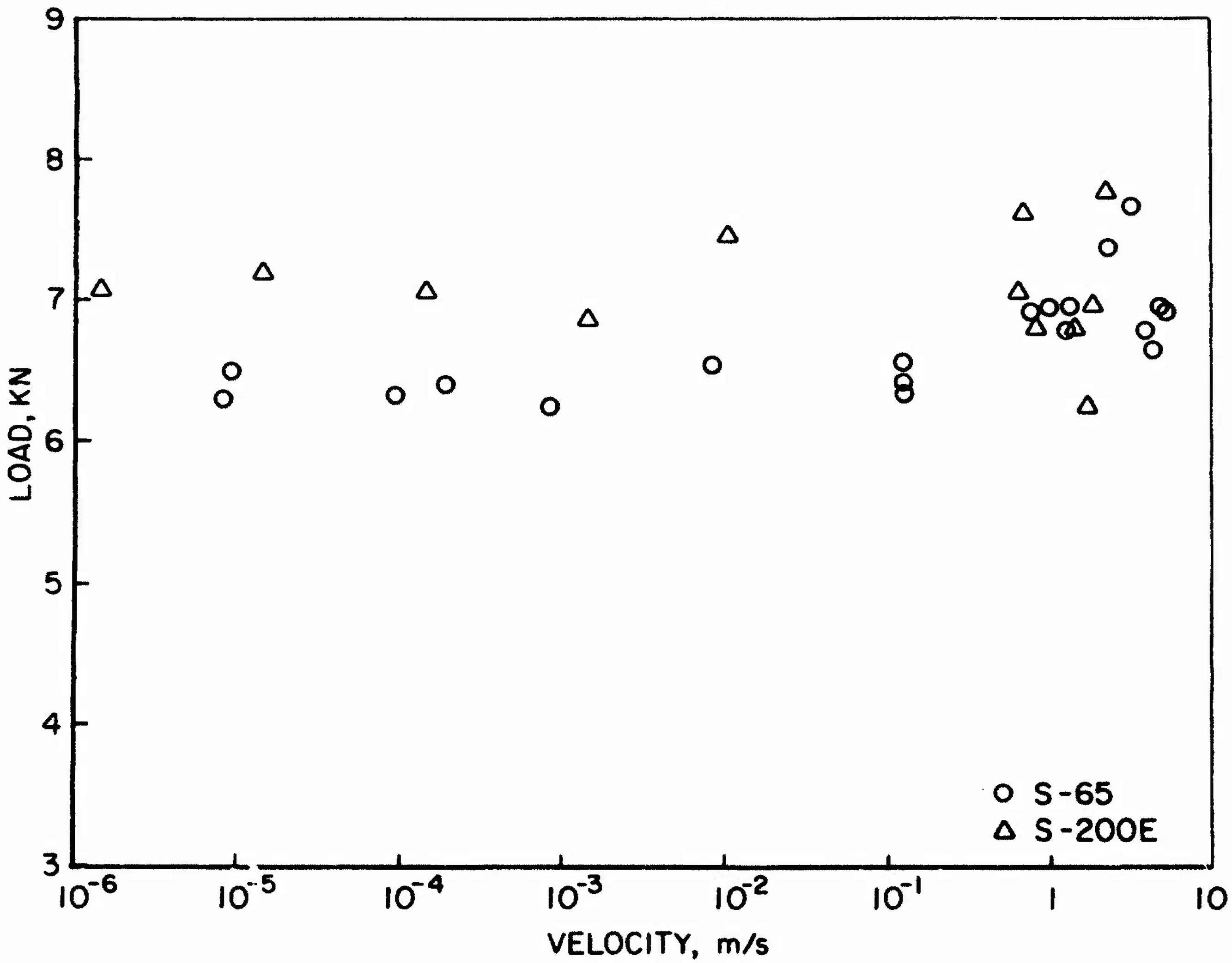


Figure 9. Maximum Load, S-65 and S-200E

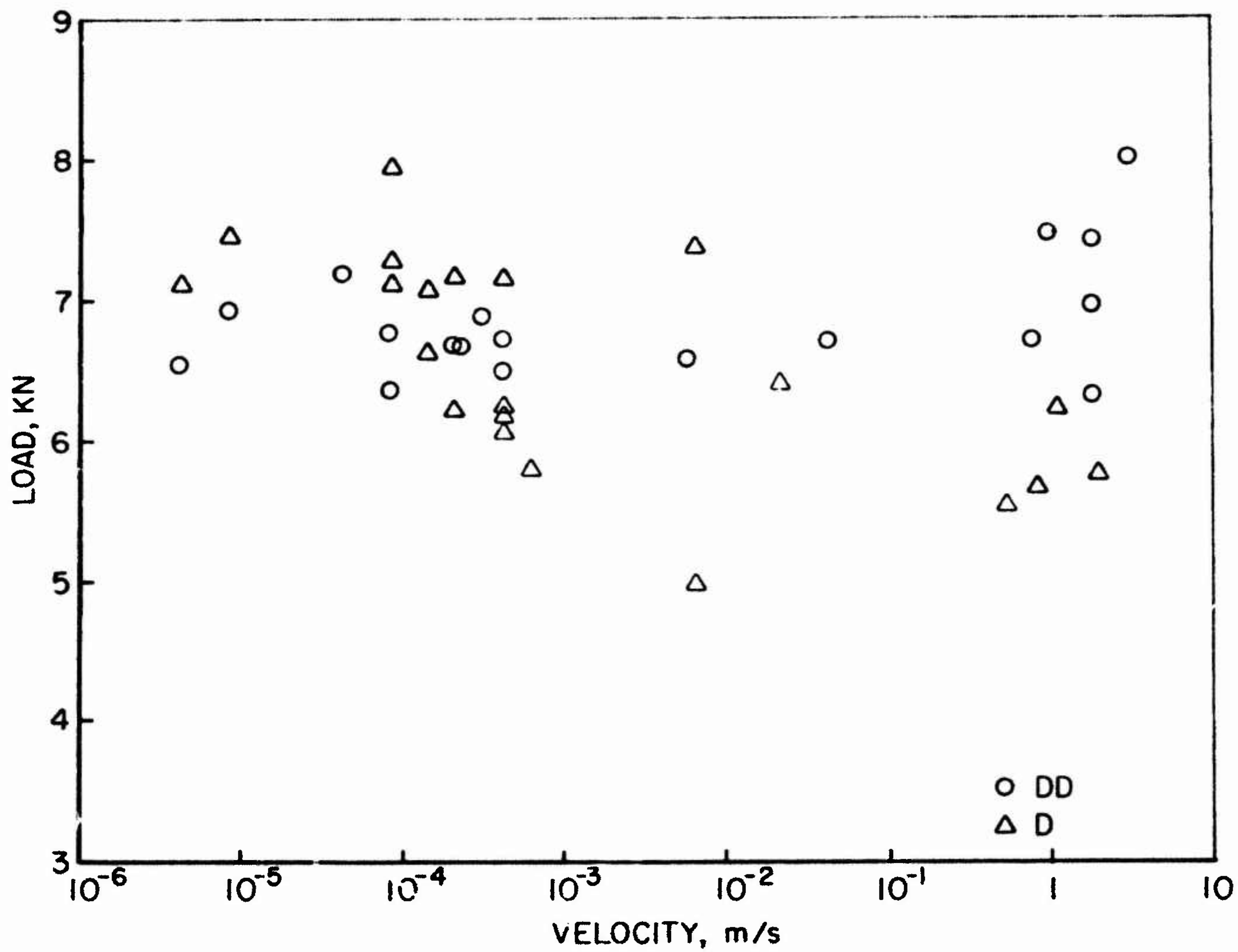


Figure 10. Maximum Load, D and DD

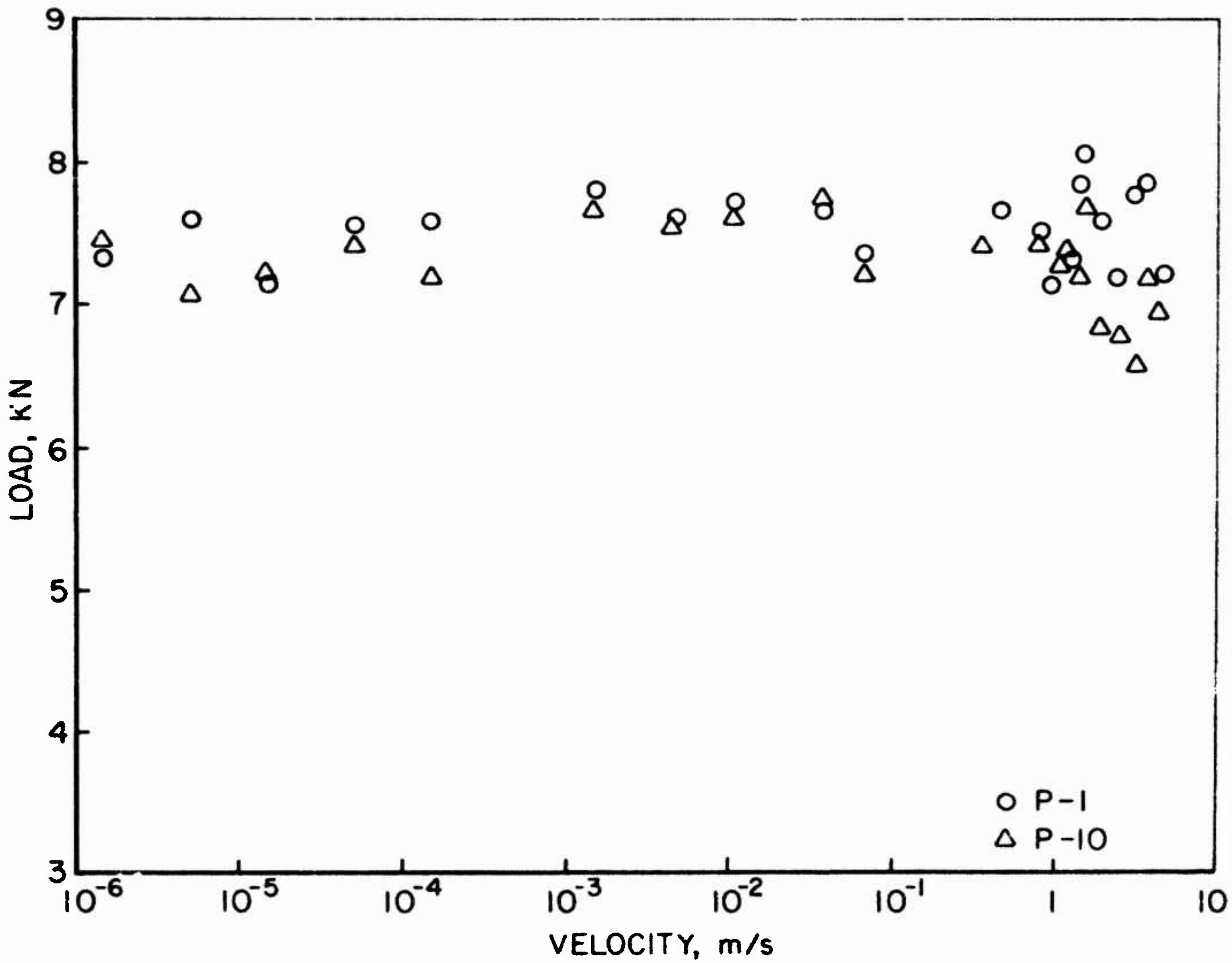


Figure 11. Maximum Load, P-1 and P-10

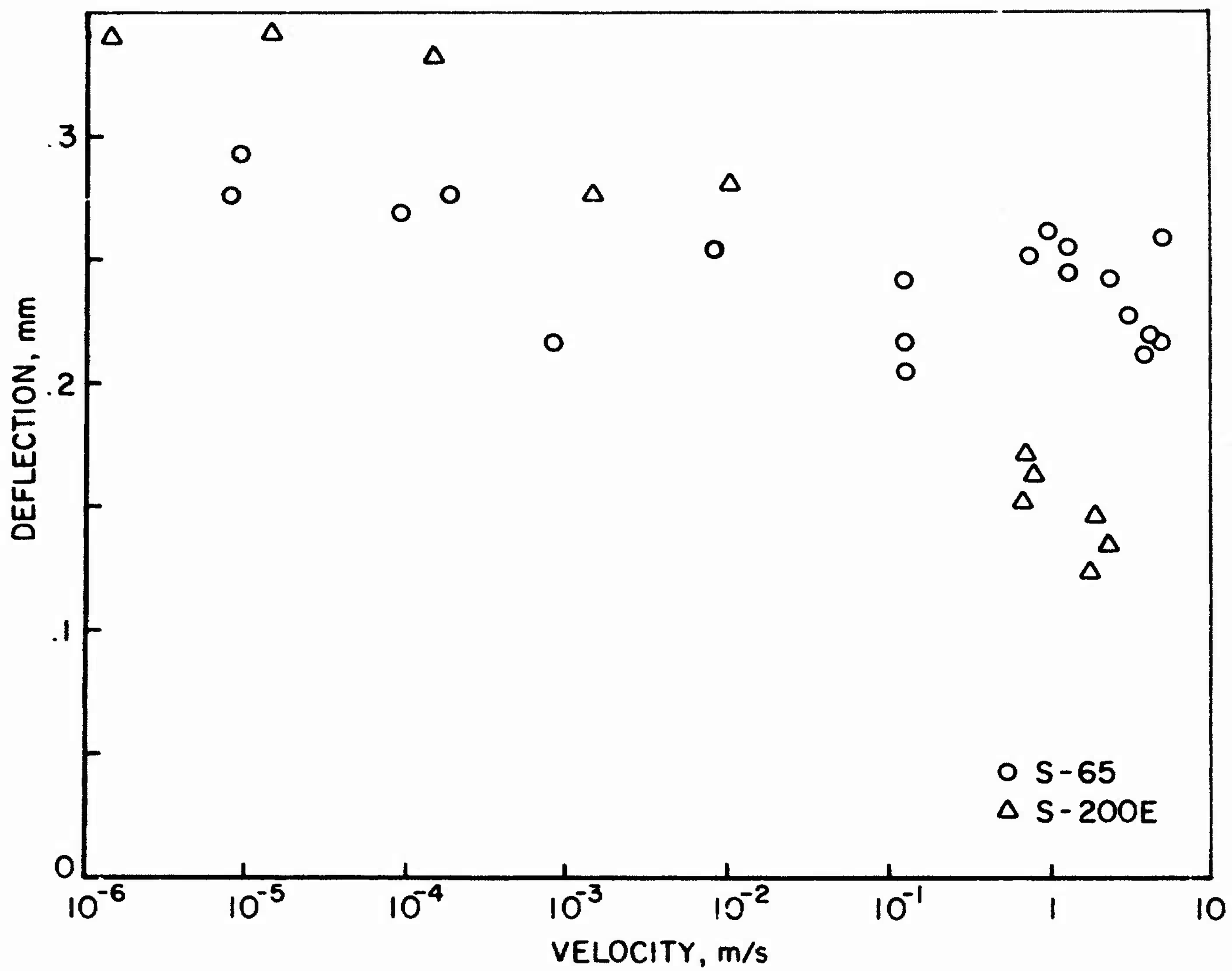


Figure 12. Maximum Deflection, S-65 and S-200E

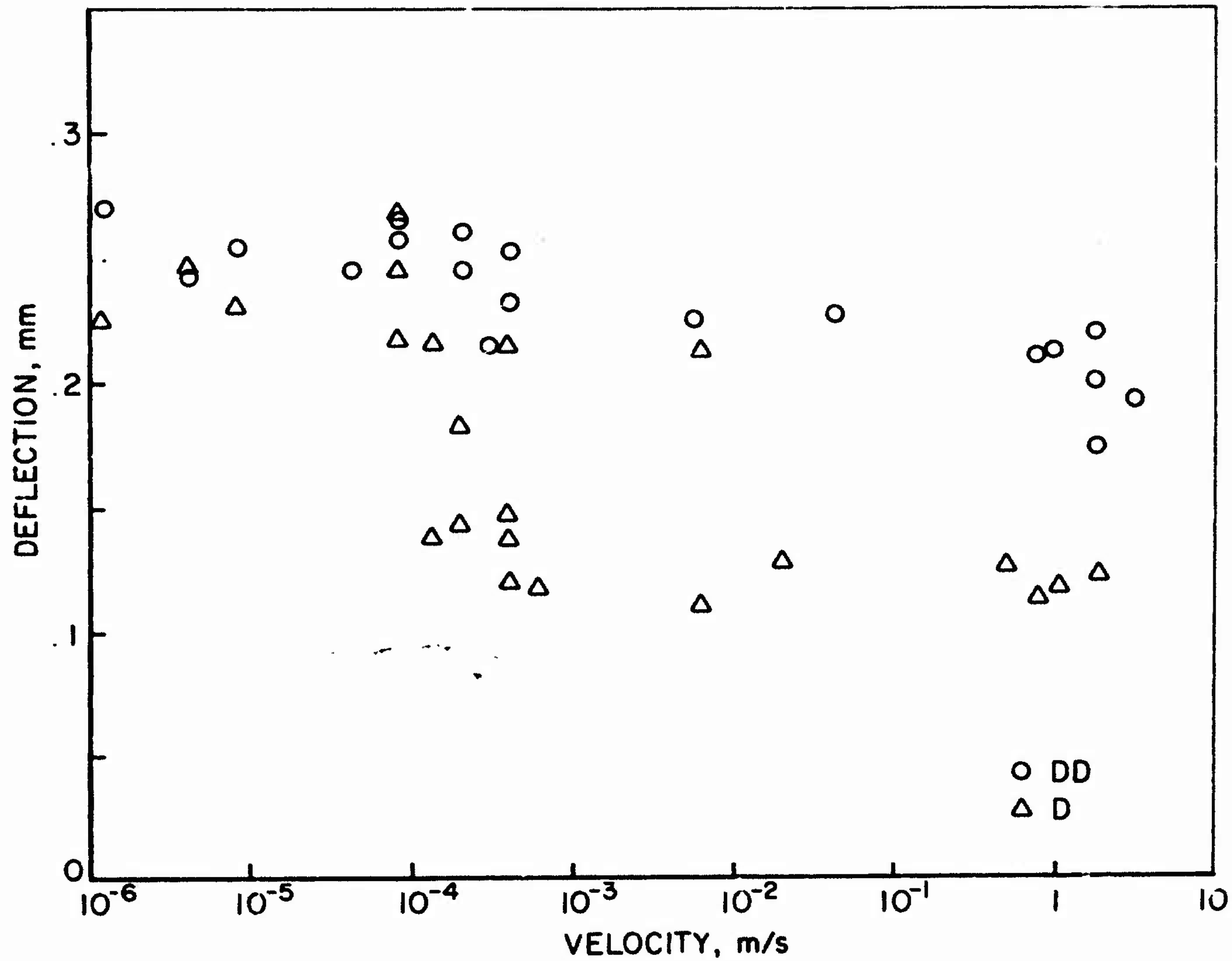


Figure 13. Maximum Deflection, D and DD

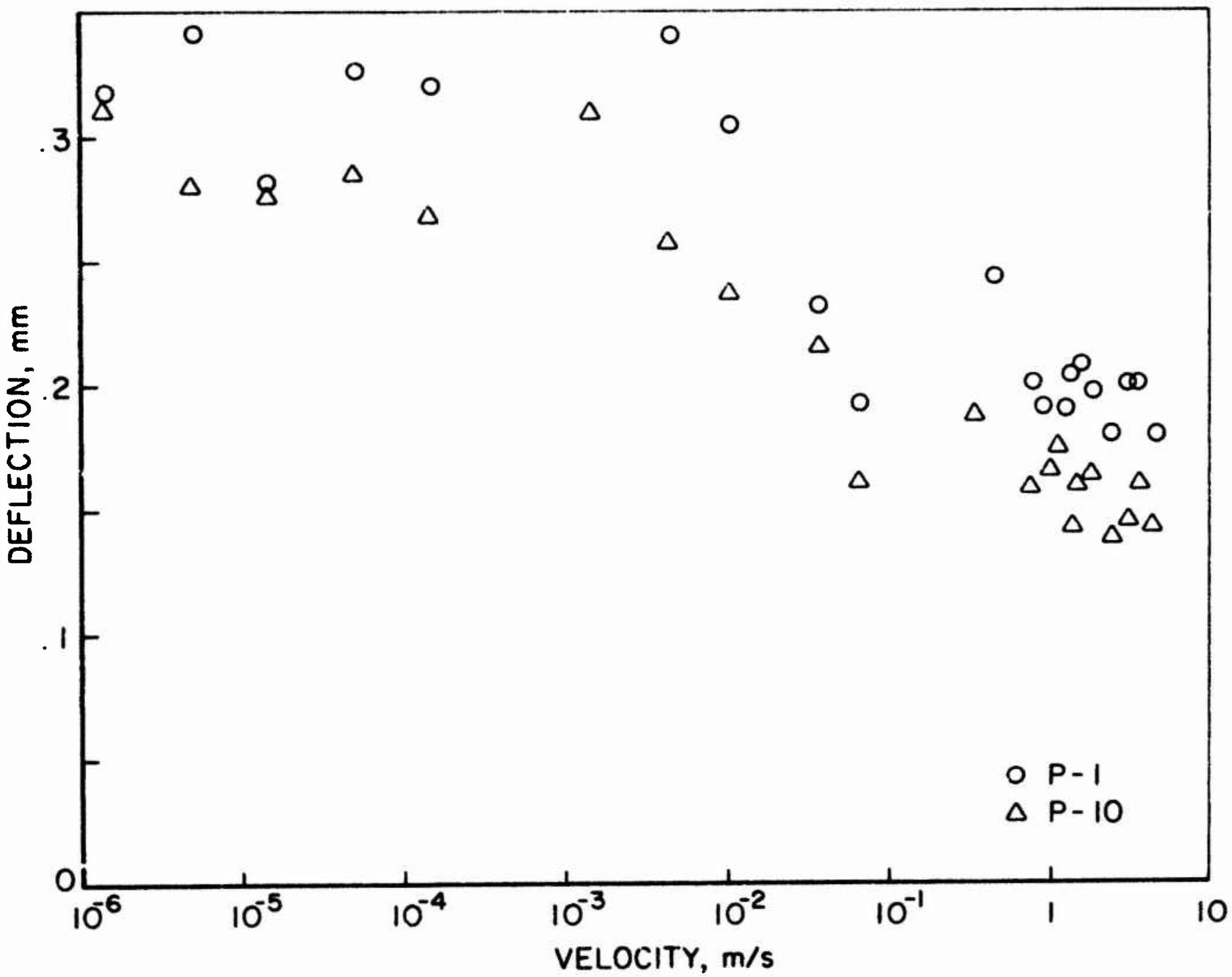


Figure 14. Maximum Deflection, P-1 and P-10

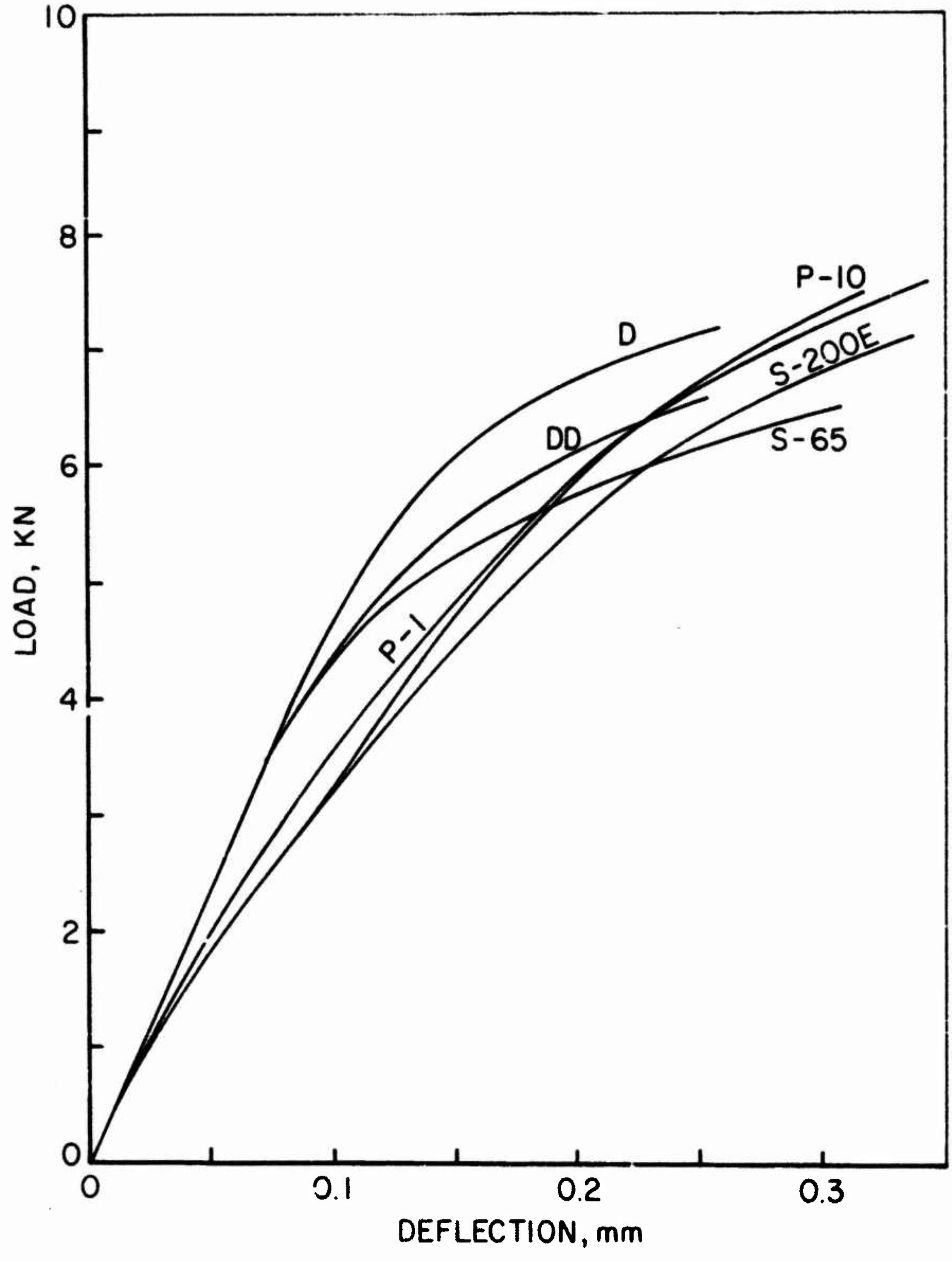


Figure 15. Typical Quasi-Static Load-Deflection Curves

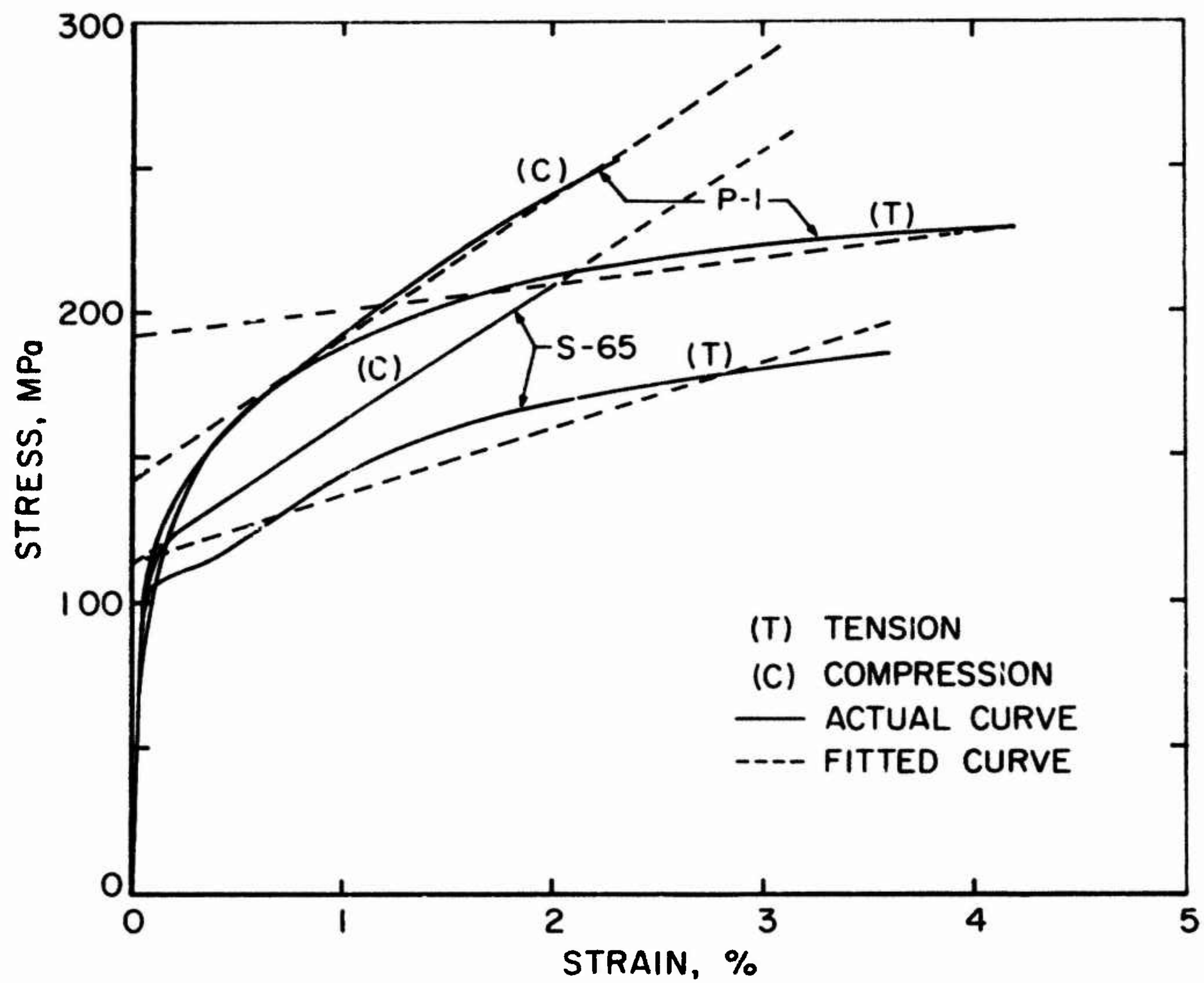


Figure 16. Uniaxial Tension and Compression Stress-Strain Curves

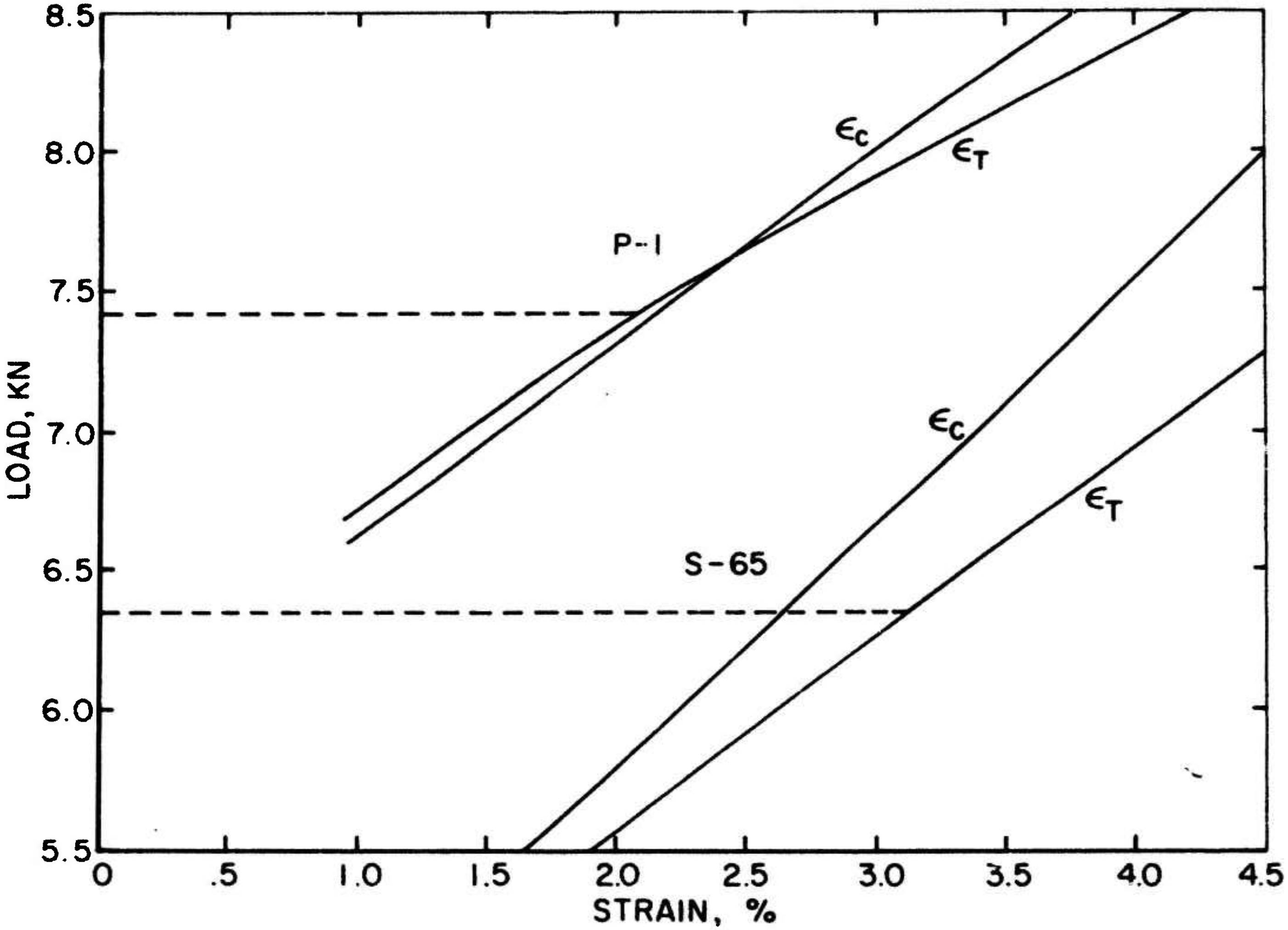


Figure 17. Result of Calculations Based on Elementary Beam Theory

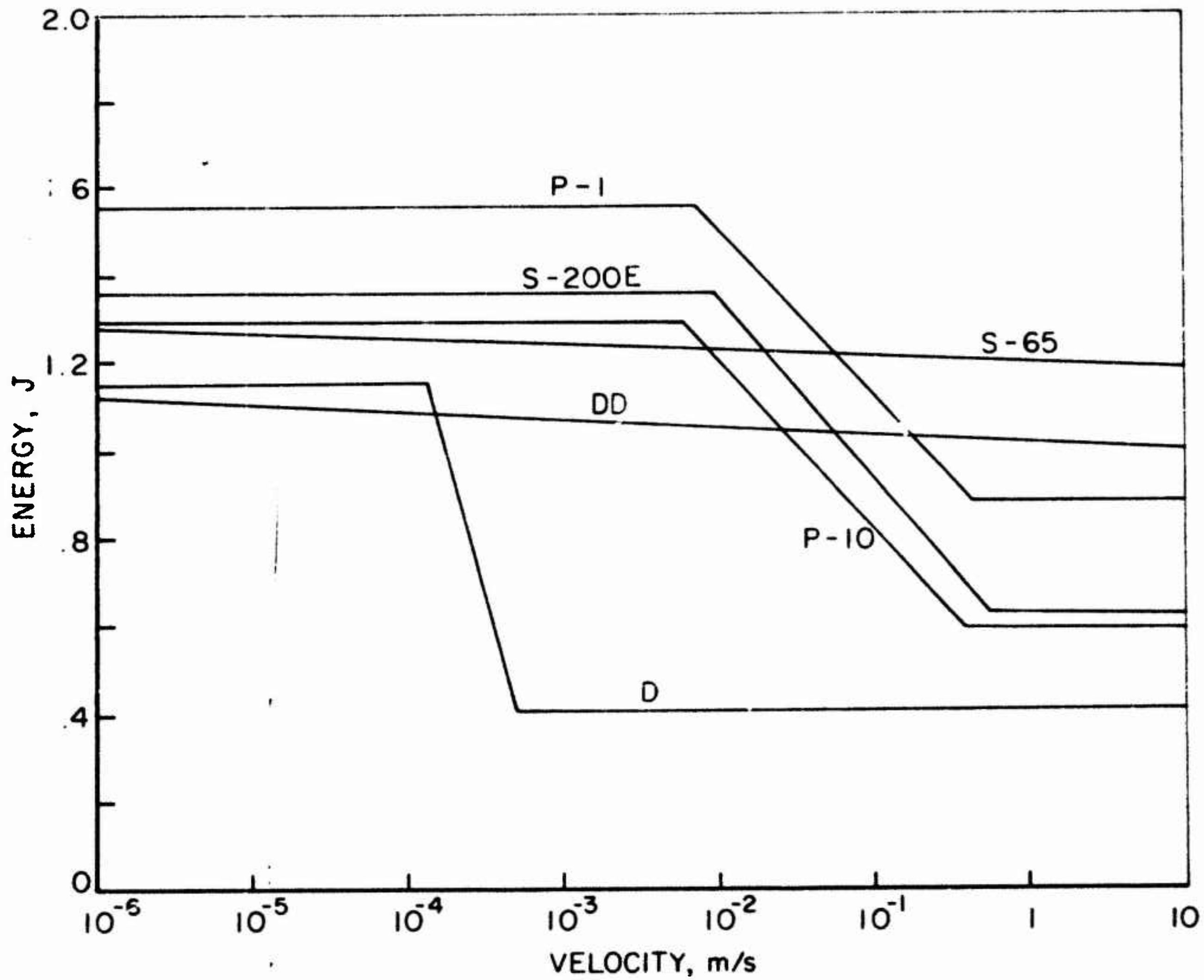


Figure 18. Absorbed Energy versus Velocity for Six Grades of Beryllium